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Space Shuttle Main Engine Start with Off-Nominal Propellant Inlet Pressures

Michael Bradley
Boeing Defense & Space Group
Rocketdyne Division
Canoga Park, CA

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START WITH OFF-NOMINAL PROPELLANT INLET PRESSURES

Michael A. Bradley*
Boeing Defense & Space Group, Rocketdyne Division
Canoga Park, Ca

ABSTRACT

This paper describes Rocketdyne's successful analysis and demonstration of the Space Shuttle Main Engine (SSME) operation at off-nominal propellant inlet conditions during the Reusable Launch Vehicle (RLV) evaluation tests. The nominal inlet condition range is: 103 to 111 psia and 170.5 to 178°R for the oxidizer and 43 to 47 psia and 37 to 40°R for the fuel. The SSME start was successfully demonstrated with engine inlet pressures of 50 psia liquid oxygen (LOX) with subcooled LOX at 160°R and 38 psia fuel at 38°R. Four tests were used to incrementally modify the start sequence to demonstrate the final goal.

INTRODUCTION

The SSME is a staged combustion cycle engine which burns liquid hydrogen and LOX, both cryogenic. Two preburners burn a fuel-rich mixture to power the high pressure fuel and oxidizer turbopump turbines. This fuel rich mixture is combined with additional oxidizer and fuel (used for coolant) and burned in the main combustion chamber (MCC) at a mixture ratio of 6 lb of oxidizer to 1 lb of fuel, (see Figure-1). The SSME is rated at 470,000 pounds thrust at rated power level, with a main chamber pressure of 3006 psia (Figure 2). Throttling and power level operation is achieved by varying the (fuel preburner oxidizer valve) (FPOV) for mixture ratio control and the oxidizer preburner oxidizer valve (OPOV) for power level control.

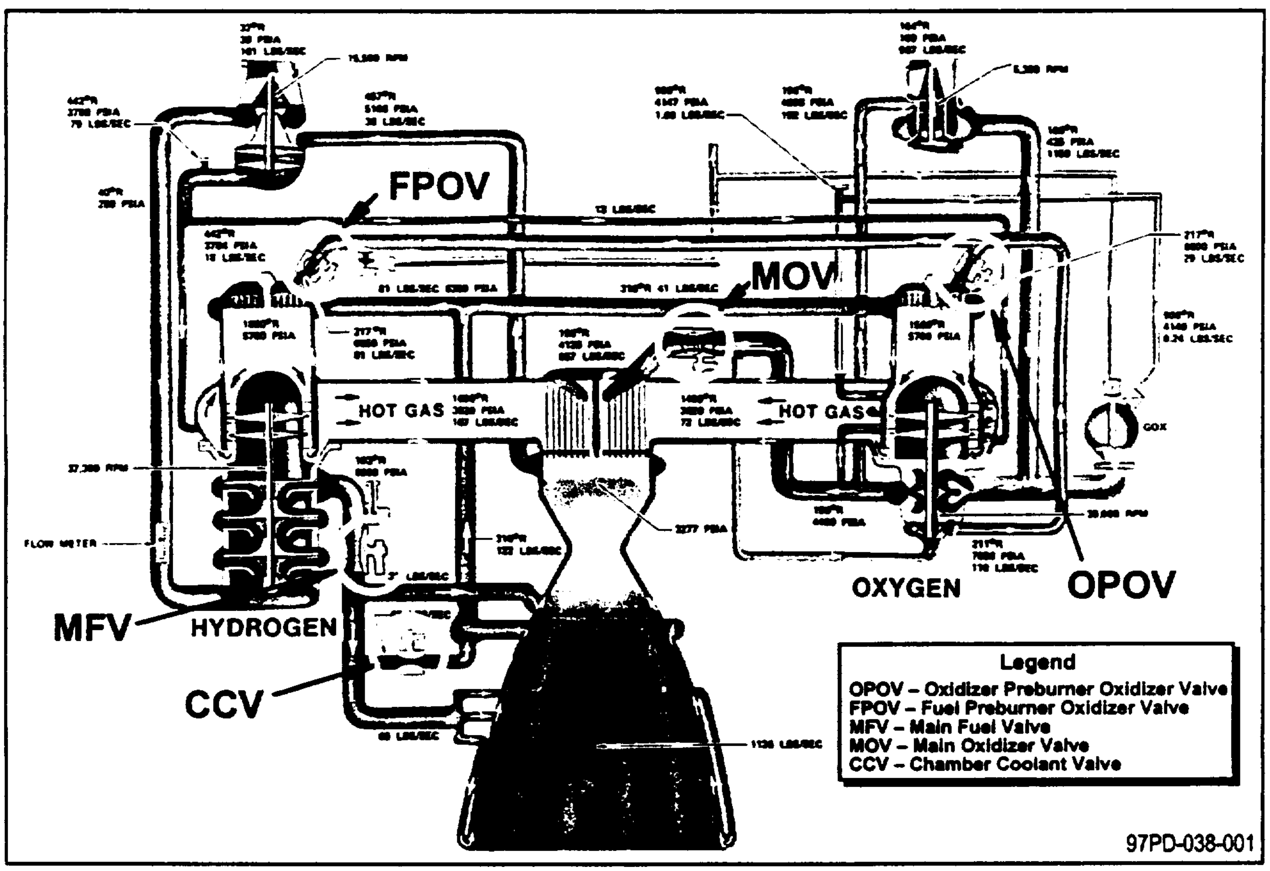

Figure-1. SSME Propellant Flow Schematic

*Member, Technical Staff

•	Rated power level (RPL) 100%	470,000 lbs
•	Rated chamber pressure	3006 psia
•	Specific impulse at altitude	453.5 seconds
•	Throttle range	65 to 109%
•	Propellants	Oxygen/hydrogen
•	Weight	7000 lbs
•	Design life	27,000 seconds, 55 starts

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Figure 2. The SSME is the First Reusable Large, Liquid Rocket Engine

The SSME relies on a difficult start mechanism, a tank head start. The staged combustion cycle is not well suited for an auxiliary powered start. An example of an auxiliary powered start device is a turbine spinner. A spinner uses high pressure gas generally from a stand alone tank. This increases weight, complicates the design, and adds failure modes. Initial energy to start the high pressure turbines spinning is all derived from initial propellant tank pressures (fuel and oxidizer) and gravity. This allows for low weight tanks, which in turn allows more weight for payload. Combining the tank head start with a staged combustion cycle consisting of: five pumps, two preburners, and an MCC results in a complicated and sophisticated start sequence, but extremely robust and reliable. Prior to test, the SSME turbopumps and ducting (down to the main propellant valves) is chilled with liquid hydrogen and LOX to cryogenic temperature to ensure liquid propellants for proper pump operation. At engine start command, the main fuel valve (MFV) is opened first to provide a fuel lead to the engine (Figure 3). The three oxidizer valves sequence the main events during the crucial first 2 seconds of start. The FPOV is ramped to 56% to provide LOX for ignition in the fuel preburner (FPB) to provide initial turbine torque. Fuel side oscillations which occur due to heat transfer downstream of the initially chilled system result in flowrate dips. These fuel flow dips can lead to damaging temperature spikes in the FPB as well as oxidizer preburner (OPB) at ignition and in 0.5 second cycles thereafter until the hydrogen is above critical pressure. The OPOV and main oxidizer valve (MOV) are ramped open next to provide LOX for OPB and MCC ignition.

The next key event is FPB prime. Priming is the filling the system upstream of the injectors with liquid propellant. This results in increased combustion and high power. This event occurs around 1.3 seconds into start. The high pressure fuel turbopump (HPFTP) speed is checked at 1.24 seconds into start to ensure it will be at a high enough level before the next key event which is MCC prime, which is controlled by the MOV. When MCC primes, an abrupt rise in backpressure on the pump/turbine occurs. If flowrate through the pump at this time is not high enough (high speed), then the heat imparted to the fluid as it is being pumped can vaporize it, leading to unsatisfactory flow in the engine, and subsequent high mixture ratio burnout in the hot gas system. This occurs if the MCC primes too early or HPFTPspeed is abnormally low. If the MCC primes too late, the HPFTP may accelerate too fast due to low backpressure after FPB prime and tear itself apart. The MCC prime normally occurs at 1.4 seconds. The OPB is primed last since it controls LOX flow and a strong fuel lead and healthy fuel pump flow is desirable to prevent engine burnout due to a high mixture ratio. The OPOV provides minimal flowrate during the early part of the start to force the oxidizer to prime last at 1.6 seconds into start. Again, the fuel side oscillations (FSO) influence temperature spikes in the OPB and must be sequenced around, prior to the MCC prime which raises the fuel pressure above critical in the

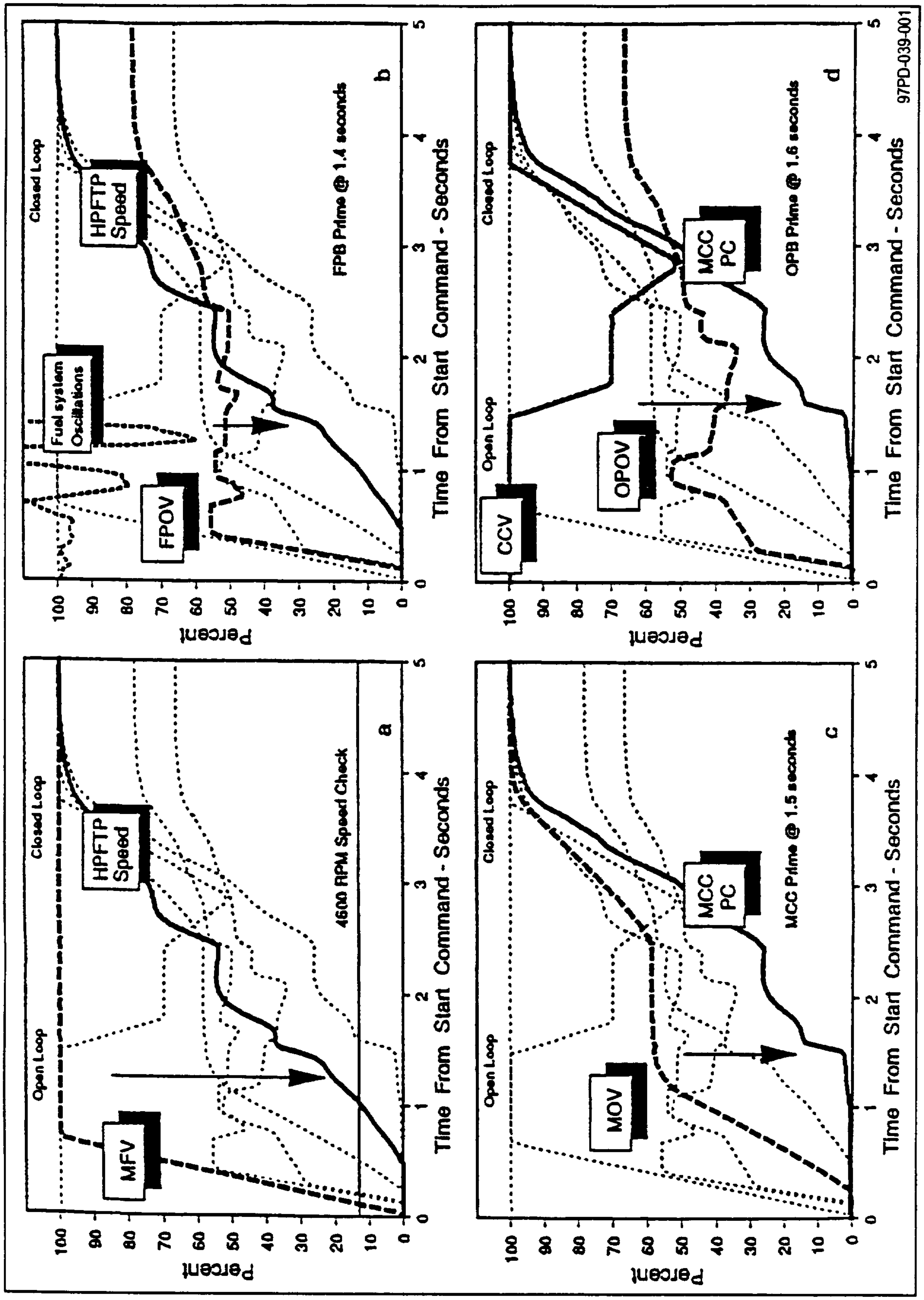

Figure 3. SSME Start Sequence

fuel system. At two seconds into start, the propellant valves are sequenced to provide 25% of rated power level (RPL). At this point, additional checks are carried out to ensure engine health, and a subsequent ramp to mainstage at 2.4 seconds is done using closed loop control. During the first 2.4 seconds of start, the engine is in an open loop mode, but proportional control of the OPOV is used based on MCC pressure.

BACKGROUND

The RLV program has a demonstrator phase entitled X-33. The X-33 phase had three vehicle contractors competing for downselect. Two of the contractors, Rockwell Space Division and McDonnell Douglas, had selected the SSME for the X-33 propulsion system. Based on the expected mission profiles a test program was designed to demonstrate expected key X-33 RLV SSME operating characteristics. Under contract NCC8-45, a joint Rocketdyne/NASA-Marshall Space Flight Center (MSFC) Cooperative Agreement, an SSME Dual Use Test program was set up to define a test plan and conduct testing on engine 3001. This engine is highly instrumented and is also referred to as the Technology Test Bed (TTB) engine. The team worked extensively with the vehicle primes to best use resources available to the program. Key objectives included operation at off-nominal low power level and with reduced engine inlet pressures. A team was created to determine and assess all technical issues, determine overall system risk, and perform all necessary steps to run the tests in a timely and safe manner. The tests at TTB were performed based on analysis completed by a team of Rocketdyne and MSFC personnel working all issues closely together with final test approval from NASA and Rocketdyne management. The tests completed at SSC had a full Rocketdyne team and a few key individuals from MSFC and Stennis Space Center (SSC) with Rocketdyne management providing final approval for test.

The SSME engine used in this test series is a Phase II engine. It has a three-duct powerhead and standard throat MCC. The HPOTP unit no. 4404 is a hydrostatic bearing pump. All additional hardware was Rocketdyne Phase II hardware in the eight tests completed for RLV demonstration.

DISCUSSION OF RESULTS

Low Start Box Demonstration Including Subcooled Propellants

In order to reduce tank weights, it was desired to demonstrate that the SSME can start at reduced inlet pressures. The goal was to demonstrate an acceptable start with a lox inlet pressure of 50 psia and a fuel inlet pressure of 38 psia with a LOX inlet temperature of 160°R (subcooled propellant). This was accomplished with nominal engine transients during Test 902-641, and the engine was ramped into mainstage successfully (Figure 4). Standard conditions are a LOX inlet pressure of 103 to 111 psia, a fuel inlet pressure of 43 to 47 psia, and a LOX inlet temperature of 170.5 to 178°R. Fuel inlet temperature remained constant (38°R) during the test series. It was decided to reduce the inlet pressures incrementally during the four test series to minimize the possibility of engine damage. Tests 902-638 to 902-641 had LOX inlet pressures of 80, 65, 57, and 50 psia respectively, fuel inlet pressures of 40, 41, 38, and 38 psia respectively, and LOX inlet temperatures of 164. 163.7, 161, 160.5°R respectively, all with nominal operation. Results are shown in Figures 5 through 8. Tests 902-639 and -640 were 1.9 second ignition tests.

Key issues that drove the modifications necessary to have a nominal start at reduced pressure were HPFTP boilout, igniter operation, and the HPFTP turbine thermal environment. Reductions in engine inlet pressure reduce engine flowrates, and therefore engine power, and slow buildup characteristics. The slowest satisfactory start transients prior to testing were those with the HPFTP/AT, which starts 200 to 400 milliseconds slower than Phase II. It was decided to keep the start transients in a family similar to the HPFTP/AT. The SSME digital transient model (DTM) was used to make predictions prior to test.

FPOV and OPOV flow area increases (***Figures 9 and 10***) were used to compensate for the reduced LOX inlet pressure, and it was decided not to compensate for the reduced fuel inlet pressure. Fuel flow is controlled by a fixed orifice and would require a mainstage operation analysis as well as a hardware change to use it to compensate for reduced fuel flow with little gain. This was felt to be unnecessary and the start was allowed to slow down with reduced fuel inlet pressure. Compensating for the reduced fuel flow with LOX was an alternative but not used because it would raise the HPFTP turbine ignition temperature spike and increase the risk of fuel turbine damage. Therefore the final family of reduced inlet pressure transients are slightly slower than with the HPFTP/AT because no attempt was made to compensate for reduced fuel flow. The digital transient model was used to determine the valve sequences needed using the FPOV and OPOV, and the MOV initial ramp rate change (***Figure 11***) needed to have acceptable margin to HPFTP stall to produce satisfactory start transients. Model predictions were very close to actuals with nominal

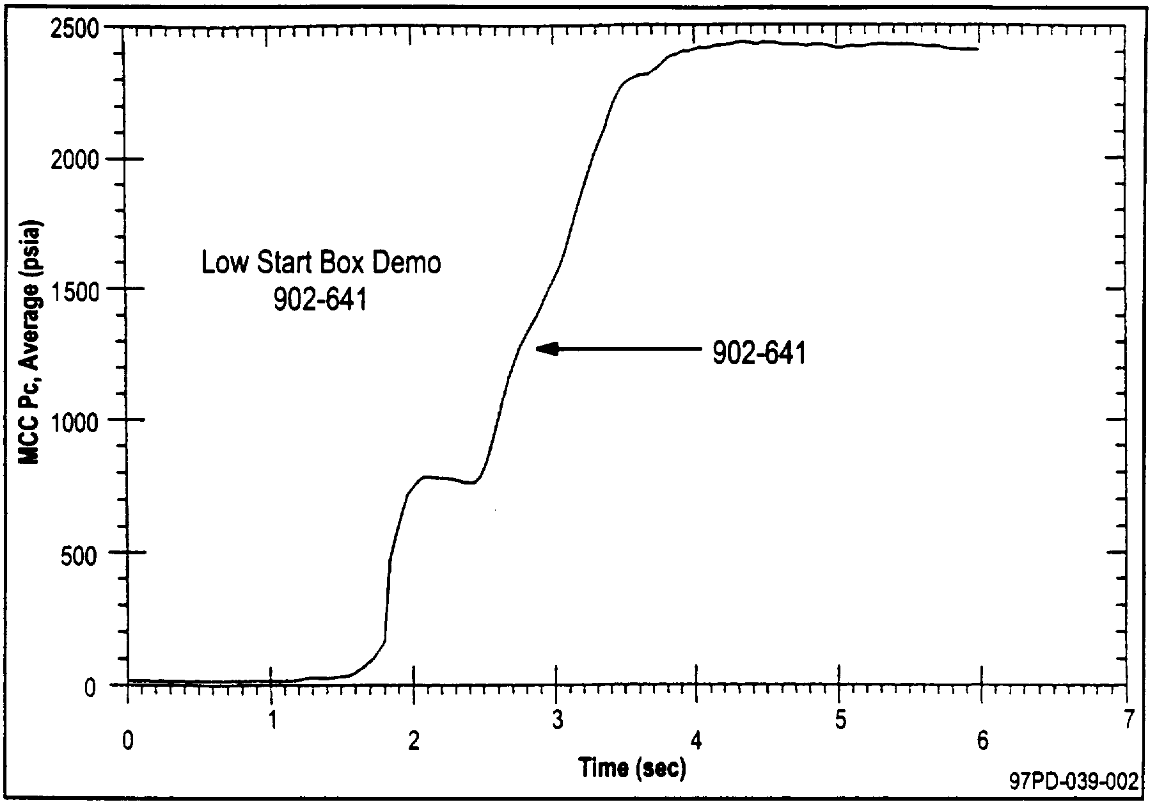

Figure 4. E3001 Transient Analysis Post Test 902-641 Fuel in PR = 38 psia LOX in PR = 50 psia

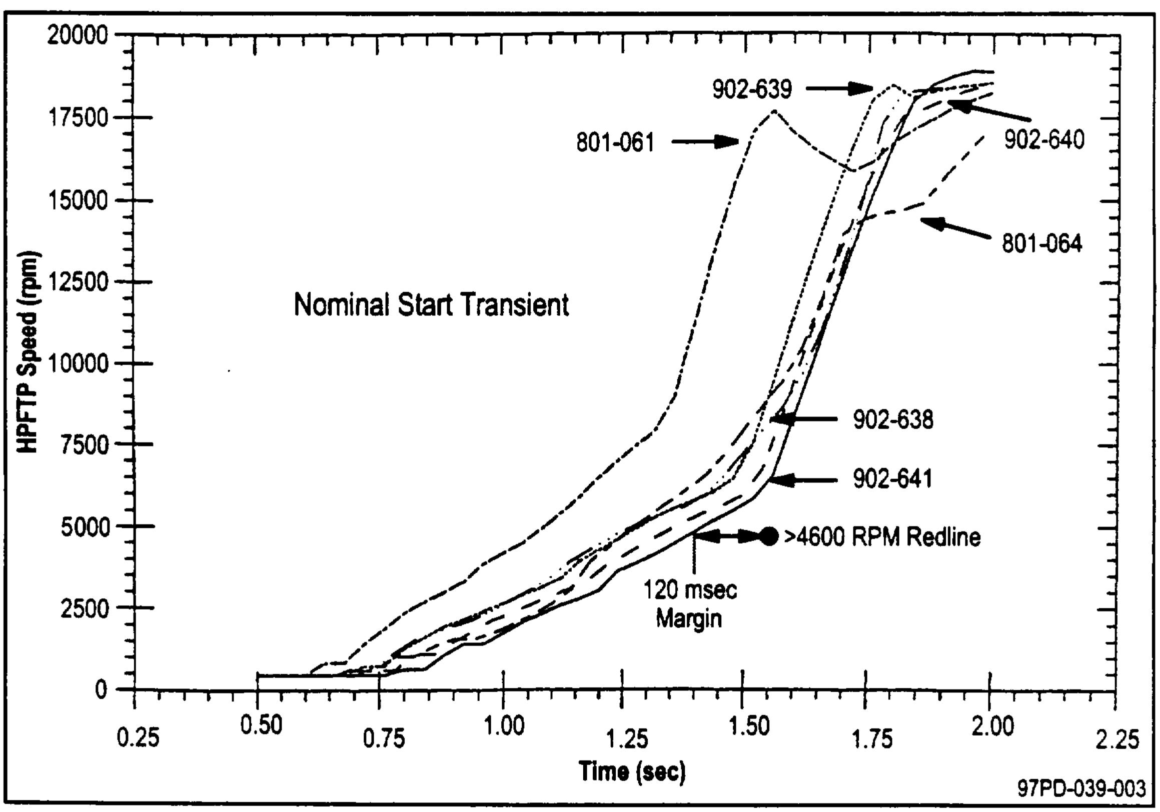

Figure 5. E3001 Transient Analysis Post Test 902-641 Fuel in PR = 38 psia LOX in PR = 50 psia

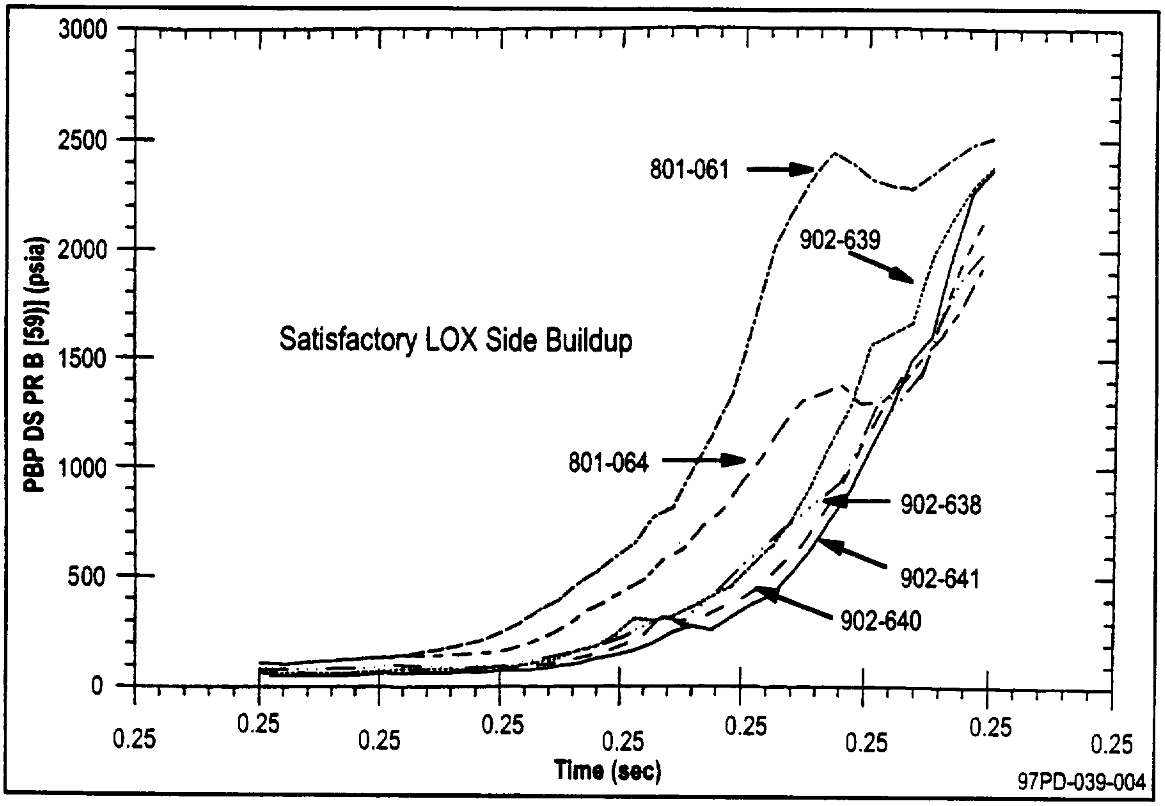

Figure 6. E3001 Transient Analysis Post Test 902-641 Fuel in PR = 38 psia LOX in PR = 50 psia

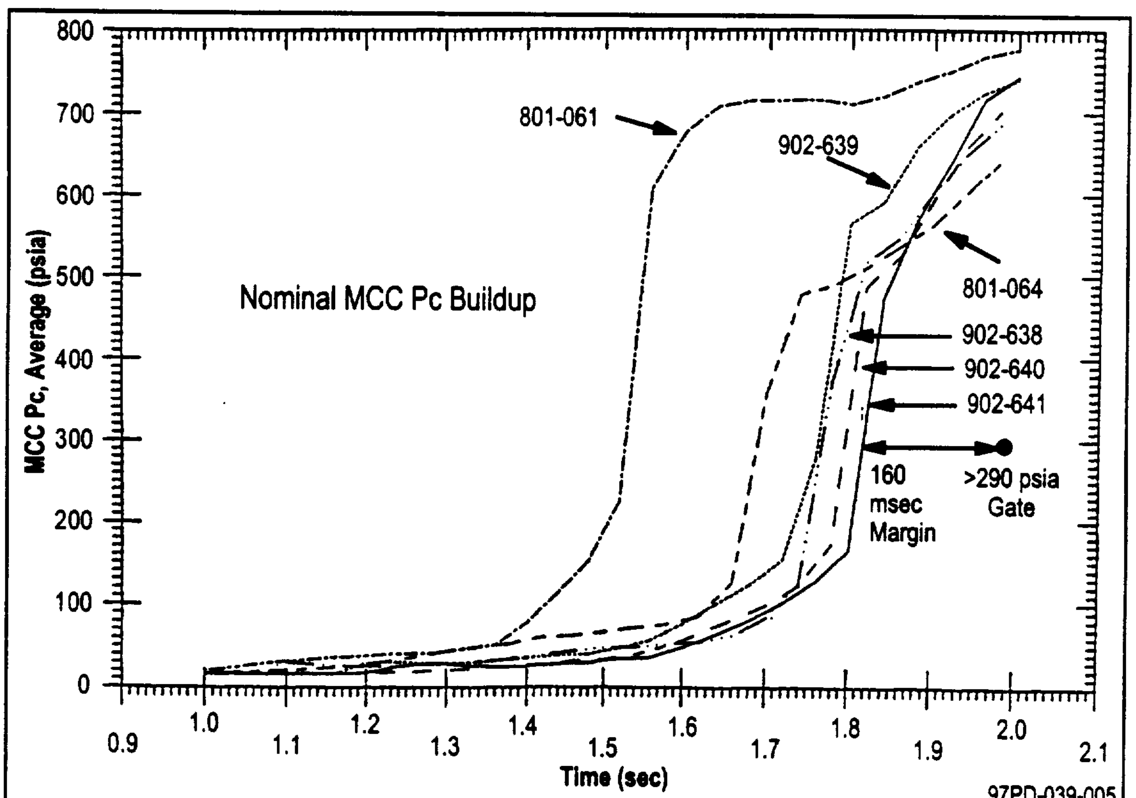

Figure 7. E3001 Transient Analysis Post Test 902-641 Fuel in PR = 38 psia LOX in PR = 50 psia

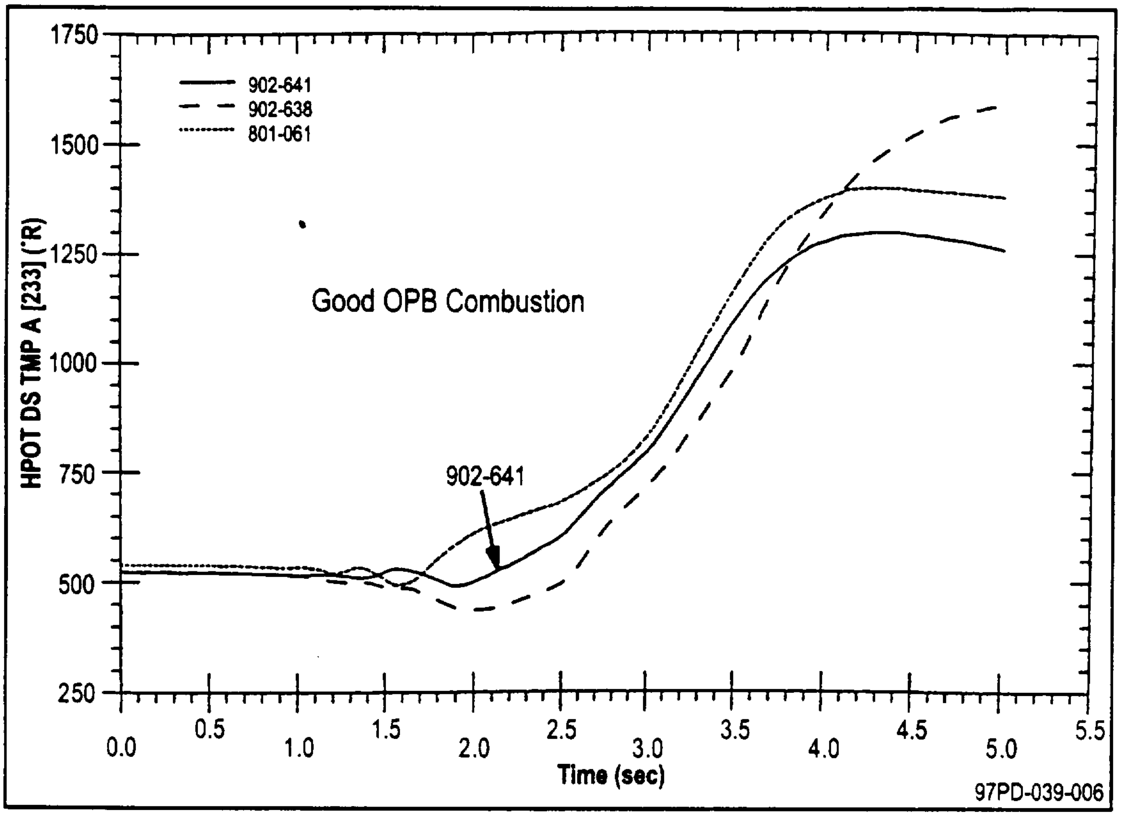

Figure 8. E3001 Transient Analysis Post Test 902-641 Fuel in PR = 38 psia LOX in PR = 50 psia

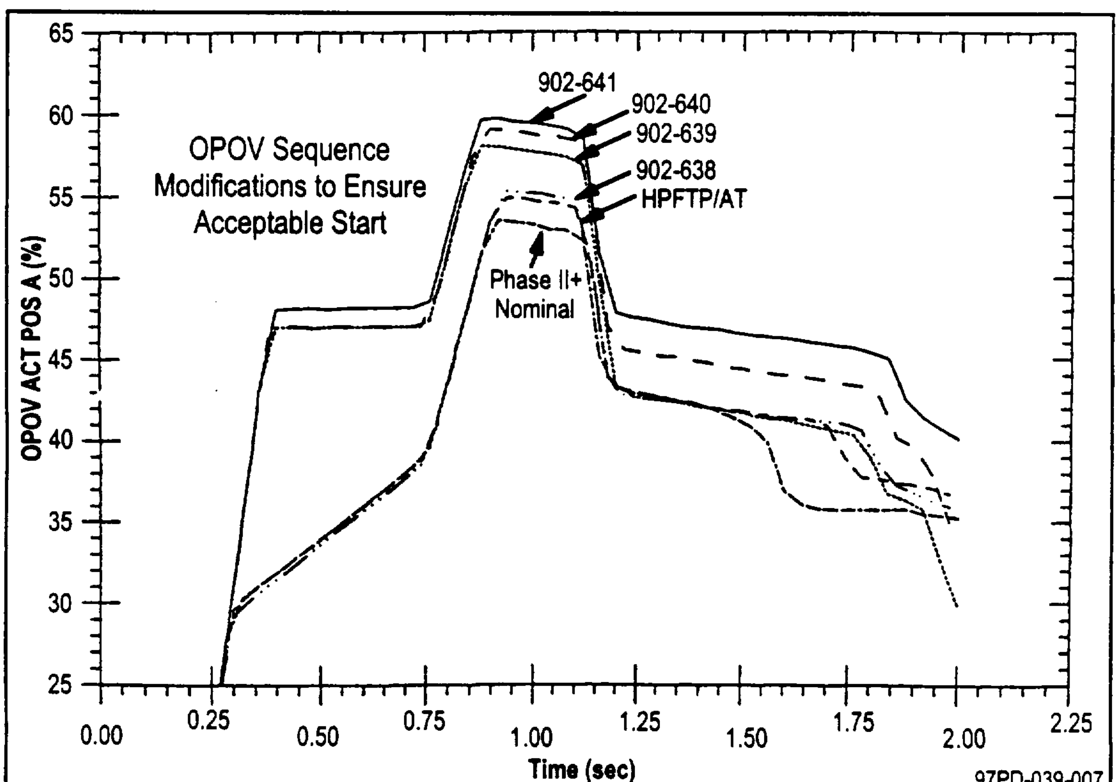

Figure 9. E3001 Transient Analysis Post Test 902-641 Fuel in PR = 38 psia LOX in PR = 50 psia

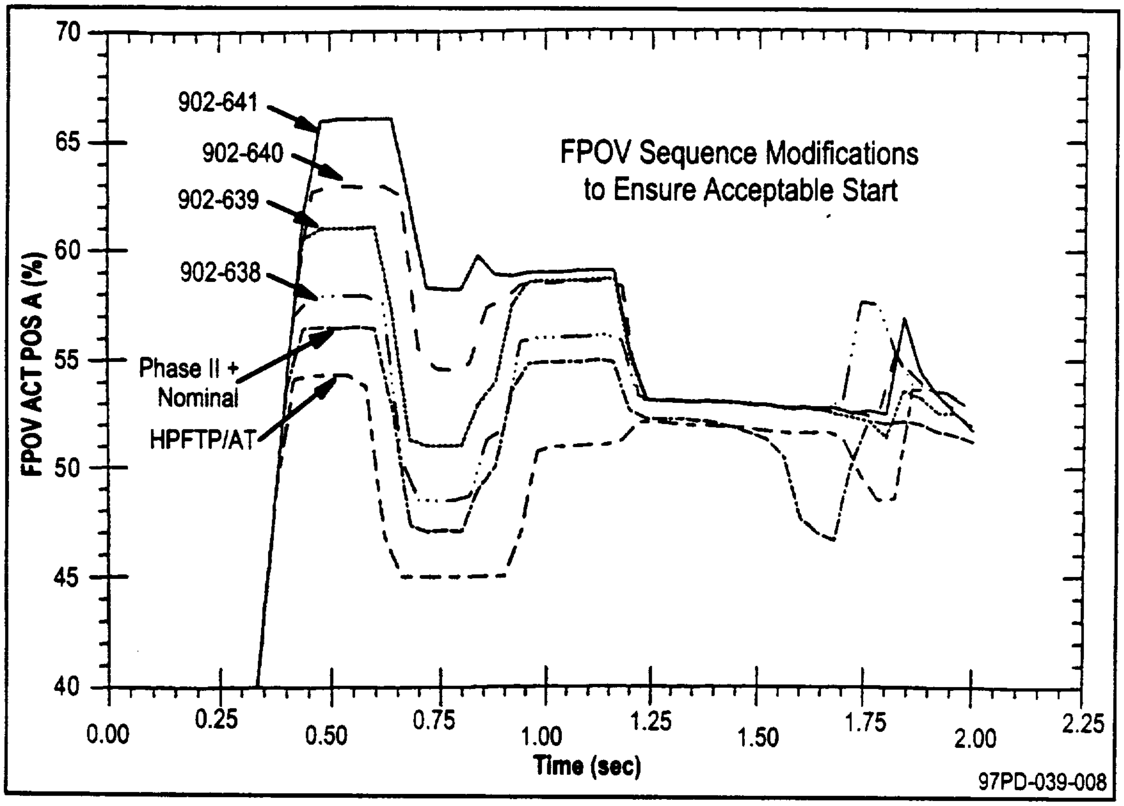

Figure 10. E3001 Transient Analysis Post Test 902-641 Fuel in PR = 38 psia LOX in PR = 50 psia

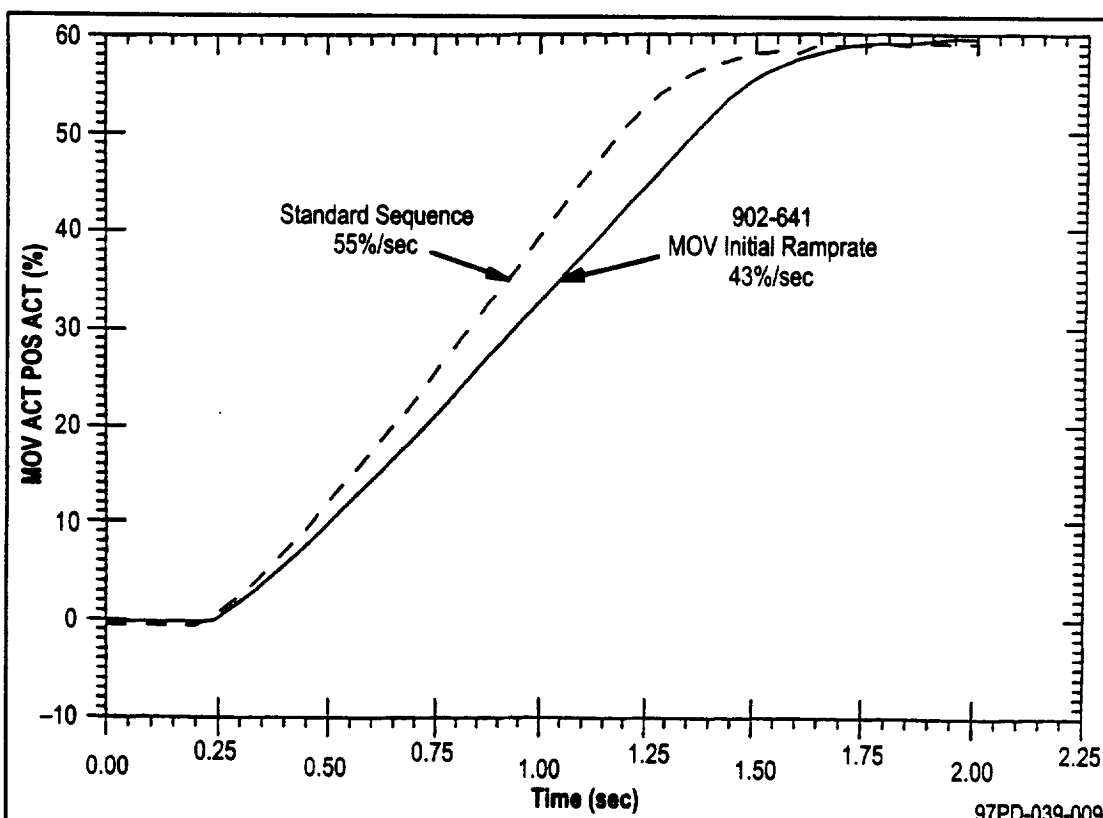

Figure 11. E3001 Test 801-065

operation during the entire test series (***Figures 12-17***). Model predictions of the start transients were very close to actuals with nominal operation during the entire start series.

The HPFTP turbine thermal profile (***Figures 18 and 19***) was satisfactory and within the nominal SSME database. HPFTP U/N 2604 has an instrumented turbine and allowed for detailed observation and verification of a nominal environment. Reductions in LOX inlet temperatures cause ignition temperatures to increase. Post-test inspections also revealed no turbine erosion.

There was risk prior to the test that the reduced flow to the igniters would not have enough energy to ignite the chambers. Analysis indicated the igniters, which work using a high mixture ratio core, would work properly. However, to reduce risk, it was decided to increase the FPB augmented spark igniter (ASI) orifice from a diameter of 0.052 to 0.057 inches to increase FPB igniter flowrate after Test 902-638. FPB ignition is the most critical early start event. All igniters worked properly and no abnormal events were observed with the reduced flow.

As predicted, prime times and engine transients are faster in buildup and turbine ignition temperatures are increased with reductions in LOX inlet temperature. An improved correlation (***Figure 20***) between LOX inlet temperature and prime times was determined based on reductions in inlet temperature during Tests 801-060 and -061. Operation was as expected during subcooled testing at SSC. No concern has been found with the effect of subcooled propellants on start transients. Overall start transients were nominal with reduced inlet pressure and subcooled lox as predicted.

CONCLUSION

The SSME is a versatile, proven rocket engine. This test program demonstrated the ability of the SSME to accommodate wide variation in safe operating ranges. The demonstrated prediction capability of the SSME digital transient was quite impressive. The benefits of this test program will have an impact on SSME operation in general far into the future. In closing, the as-advertised X-33/RLV successful operating potential of the SSME was demonstrated in test without error and to great success.

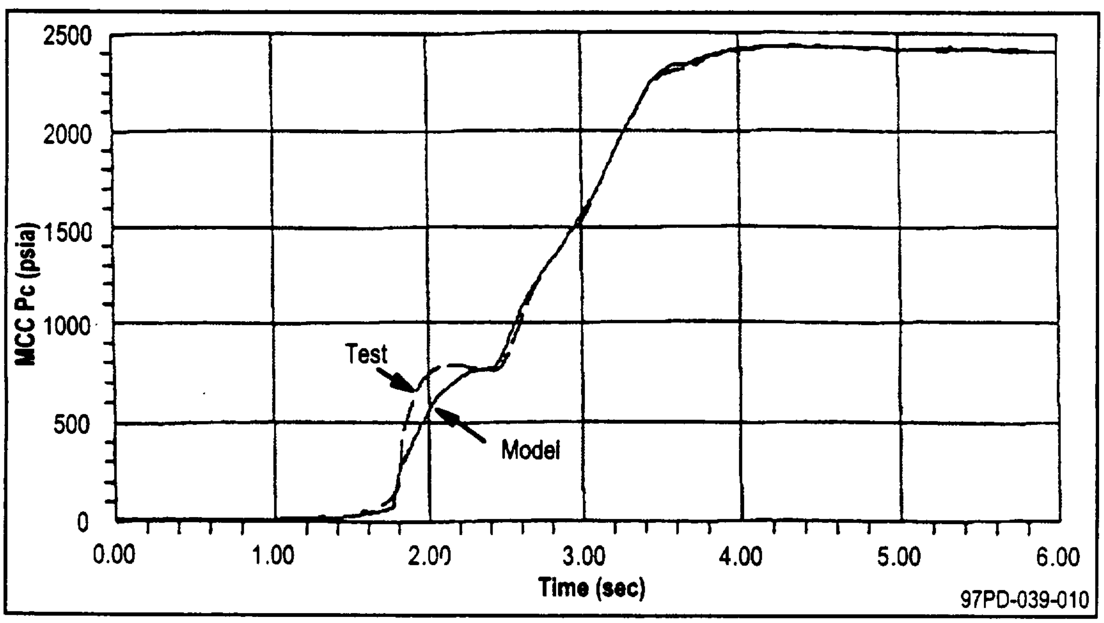

Figure 12. MCC Pc Predicted vs Actual Start to 80% RPL

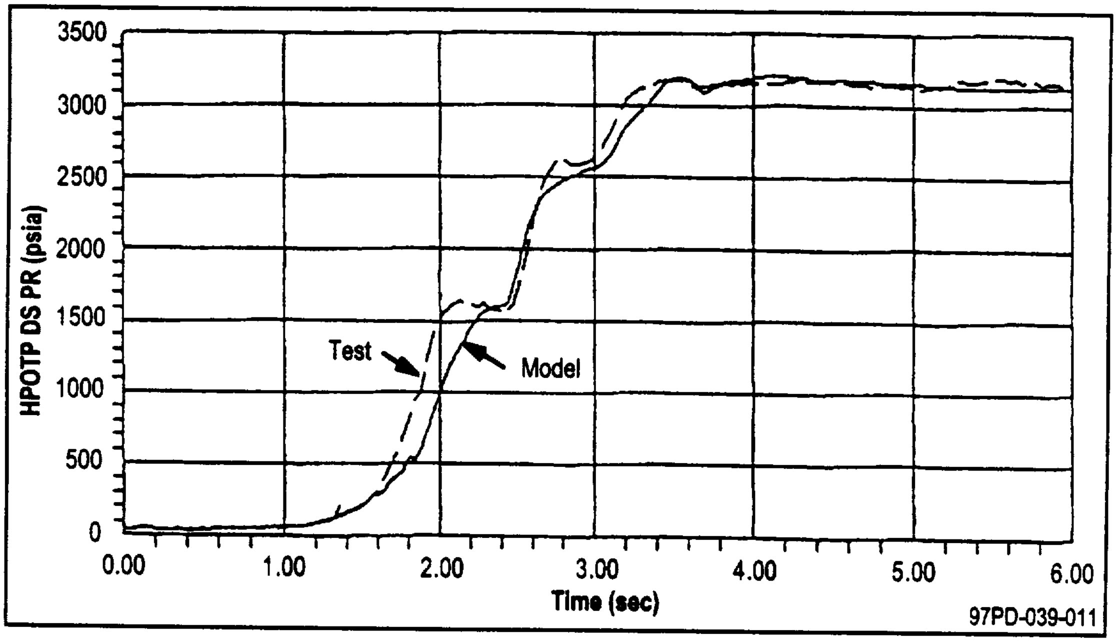

Figure 13. HPOTP DS PR Predicted vs Actual

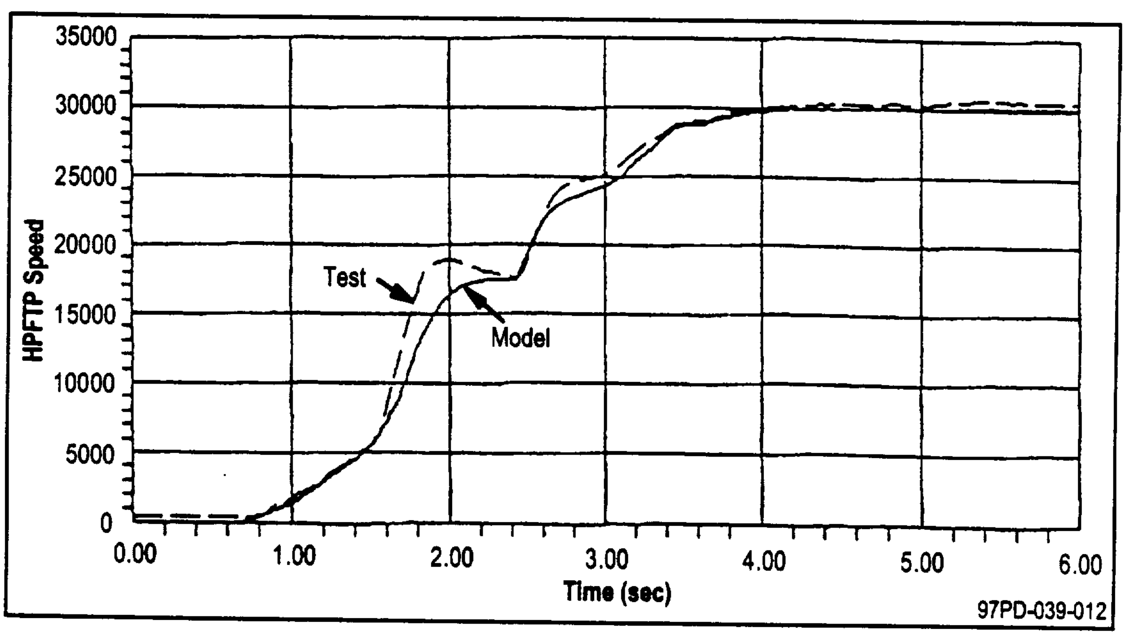

Figure 14. HPFTP Speed Predicted vs Actual Start to 80% RPL

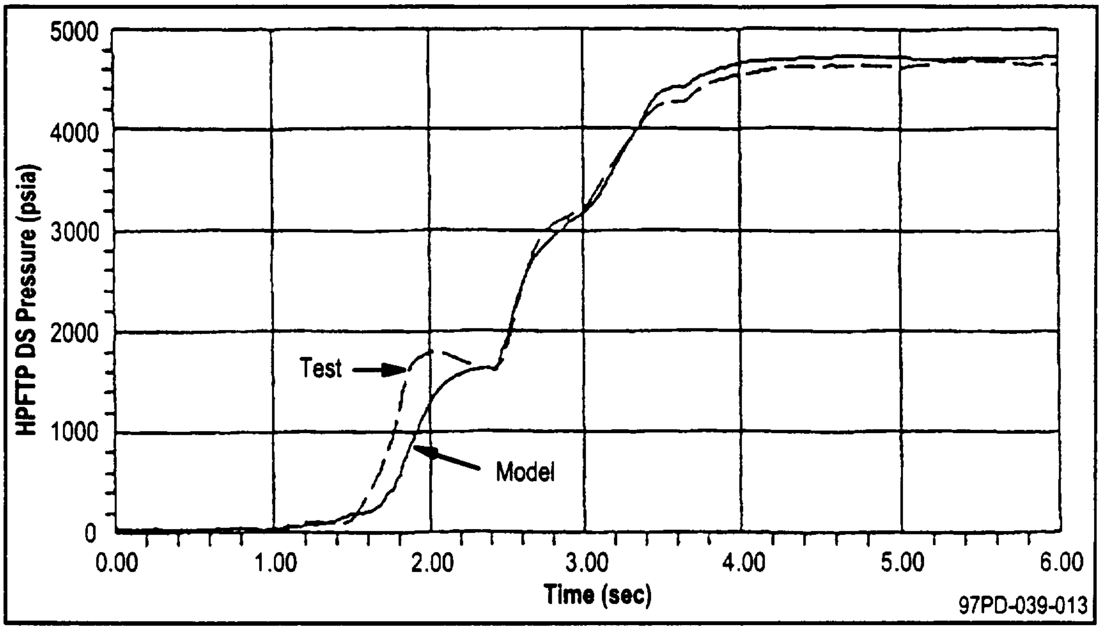

Figure 15. HPFTP DS Pressure Predicted vs Actual Start to 80% RPL

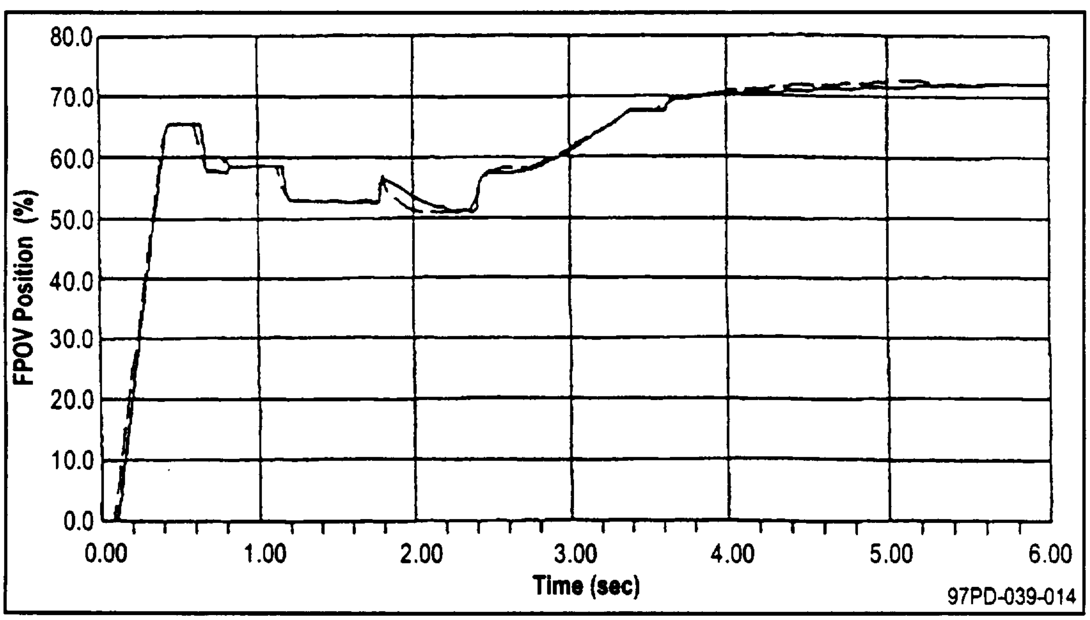

Figure 16. FPOV Position Predicted vs Actual Start to 80% RPL

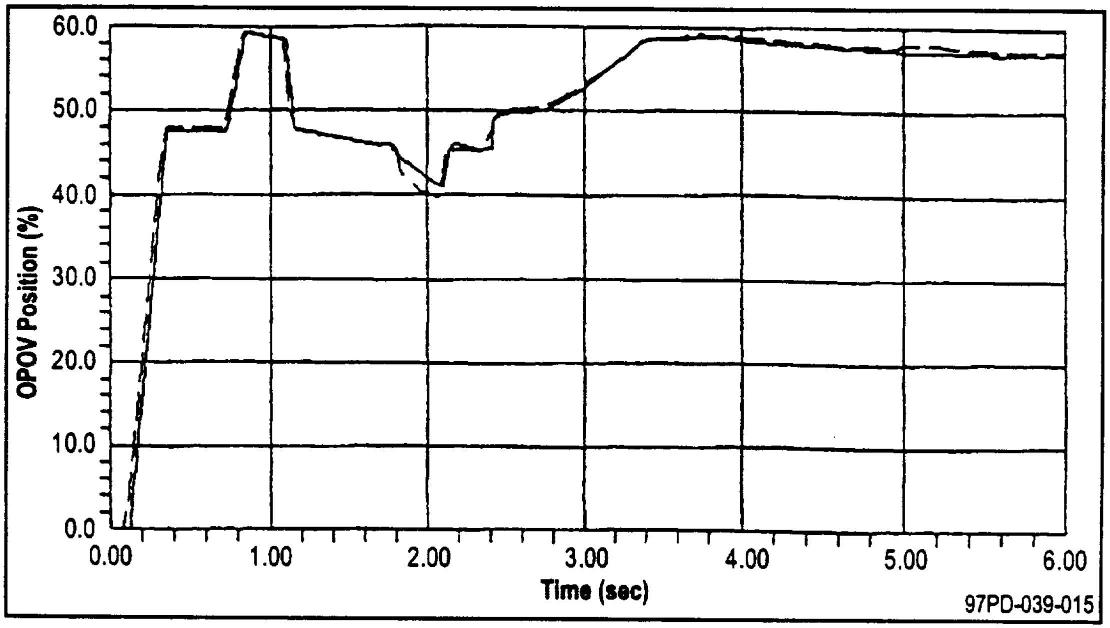

Figure 17. OPOV Position Predicted vs Actual Start to 80% RPL

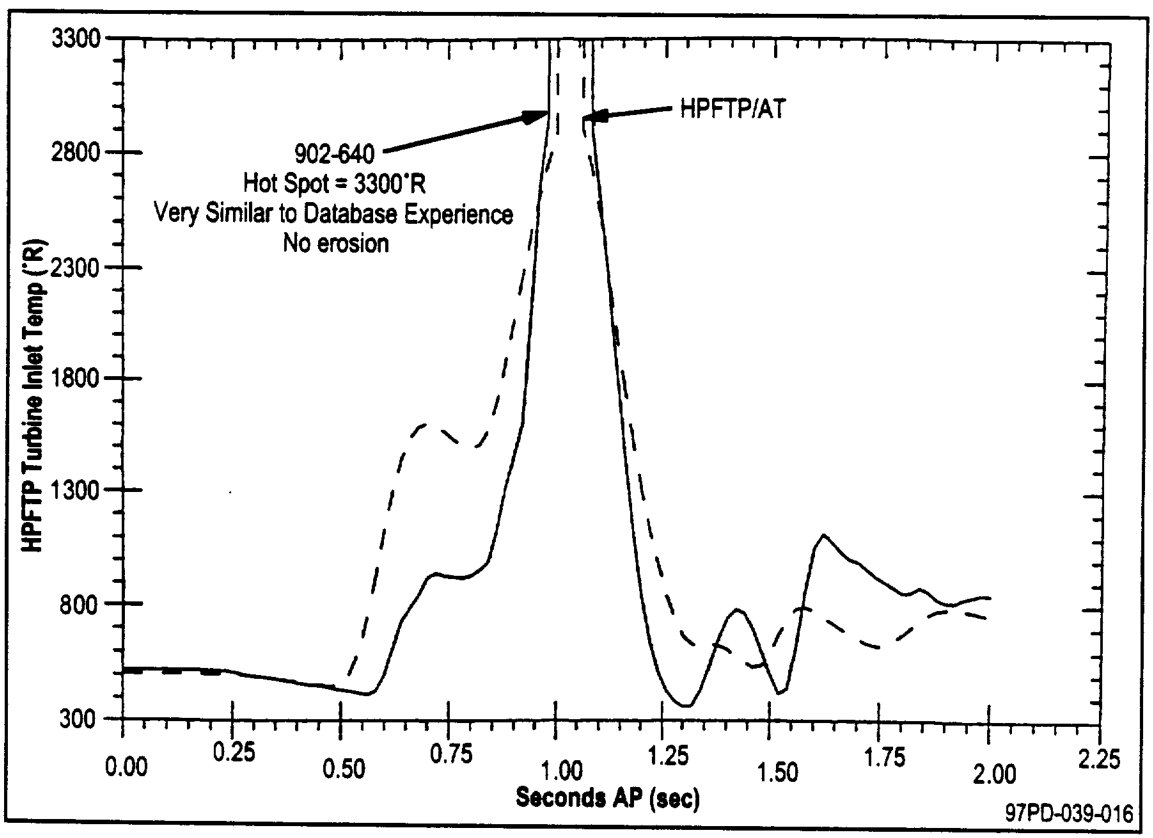

Figure 18. HPFTP Turbine Inlet Temperature 902-640

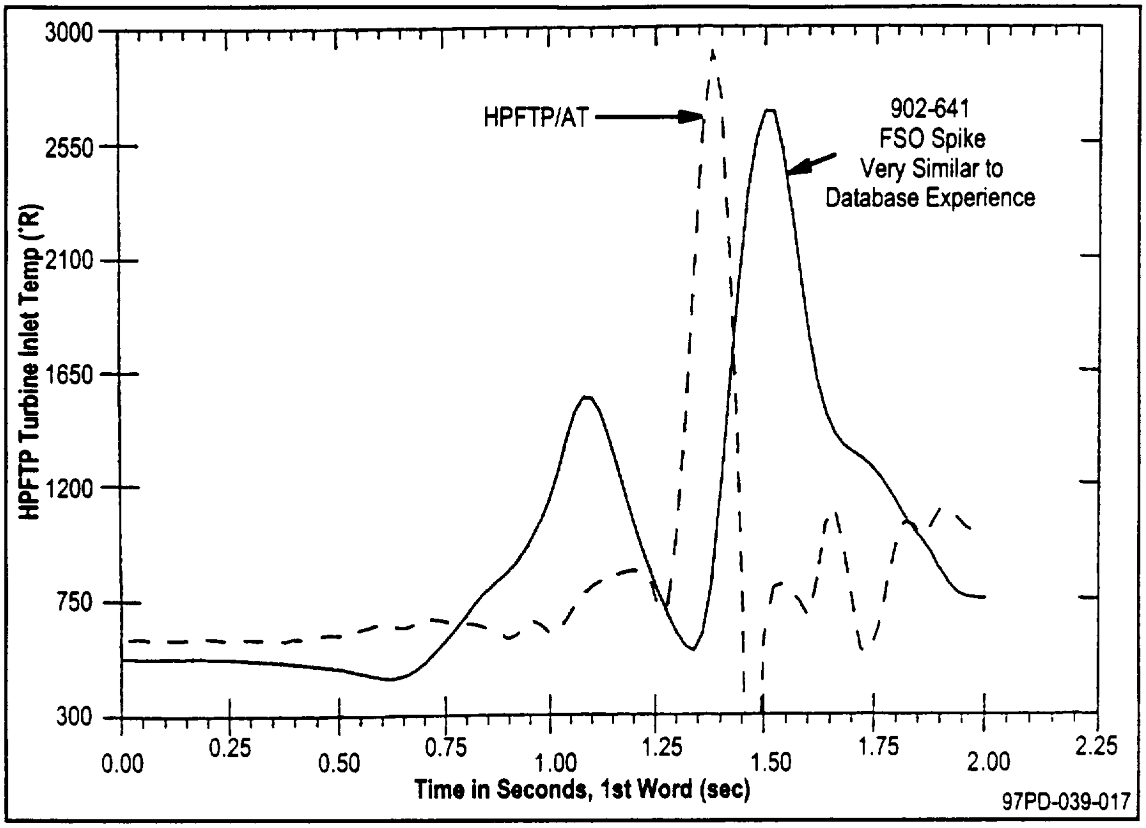

Figure 19. HPFTP Turbine Inlet Temperature 902-641

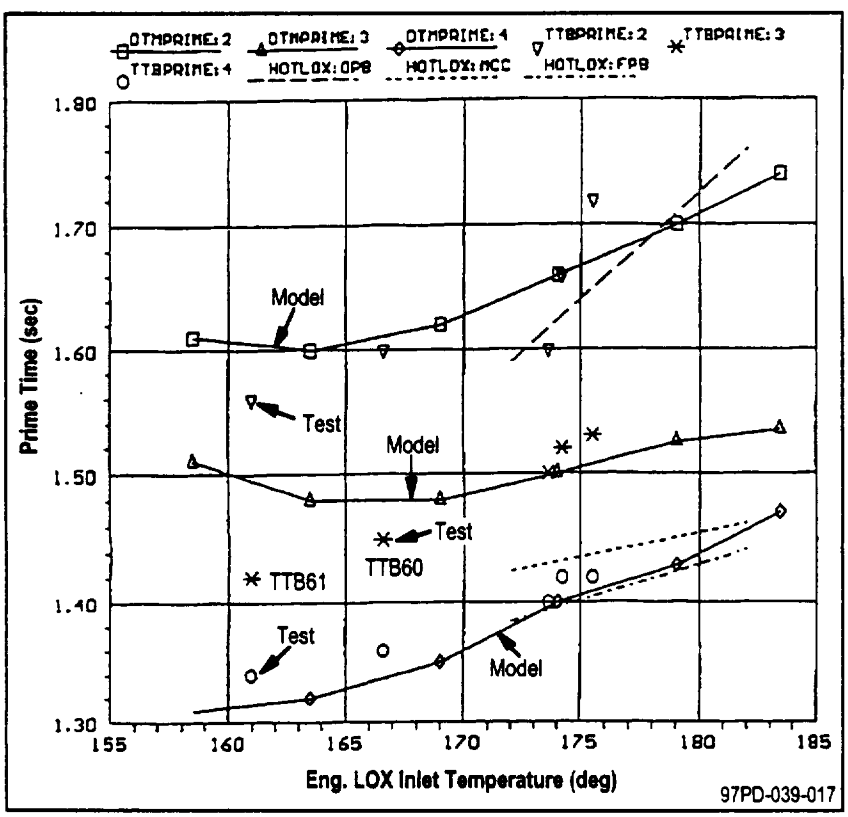

Figure 20. SSME Prime Times